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Studies of Sound Transmission in Various Types of Stored Grain for Acoustic Detection of Insects

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ABSTRACT

In developing passive acoustic systems for detecting insect infestations in bulk-stored grain, it is advantageous to understand the transmission of sound in the grain between the insects and the sensors. In the work presented here grain is shown to be a strong acoustical absorber, the attenuation coefficient increasing roughly as the square root of the frequency. Tests with soft wheat immersed in three different gases: air, argon and carbon dioxide, support an earlier conclusion that sound is transmitted principally through the gas in the passageways between the grain kernels. The speed of sound and the attenuation coefficient were measured as a function of frequency for six different types of grain: hard and soft wheat, brown rice, soybeans, corn and sorghum. It was determined that sound is transmitted over longer distances in grains with a larger inter-kernel spacing, such as corn and soybeans. Grain depth, up to several meters, appears to have little effect on sound transmission. © 1997 Elsevier Science Ltd

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INTRODUCTION

In the United States it is estimated that about 10%, or 1 billion (10^9) dollars worth, of stored grain is destroyed annually by insects. Insects also affect the quality of grain exports.[1] Grain loss to insects is much higher in some developing countries.[2] Various methods are used to control insect infestation.[3] Early detection is obviously important. A number of detection methods have been investigated.[4] For automated systems in bulk-stored grain, the most practical method appears to be acoustic detection.[5-7] To use acoustic detection effectively it is necessary to understand the transmission of sound in grain.

In a previous paper[8] it was shown that grain is a highly absorbing acoustical medium. It acts as a low-pass filter, with the attenuation coefficient increasing roughly as the square root of frequency. Strong absorption lowers background noise, but it also limits the range over which sounds of insect activity can be detected. It has been shown that the sound of a single adult red-flour beetle, *Tribolium castaneum* (Herbst), or the sound of five rice-weevil *Sitophilus oryzae* (L.) larvae can be detected at a range of about 0.1 m.[9,10] When the sensor is immersed in grain, and the background noise is low, it has been shown that a group of five adult rice weevils, confined in a volume of about 8 cm^3, can be detected at a range of about 0.5 m (Hickling and Webb, unpublished data 1992). Acoustic sensing of insects in bulk-stored grain has been performed with sensors distributed along cables.[11] This is a sampling procedure, because too many sensors are required to cover the entire volume of the grain. For a given ratio of sampling volume to the total grain volume, the number of sensors varies inversely as the cube of the range. For example, if the range of the sensors is increased by a factor of 2, the number of sensors required for a given sampling volume is reduced by a factor of 8. This illustrates the importance of sensor range in developing methods of acoustic detection in bulk-stored grain.

In a previous paper[8] it was found that sound is transmitted principally through the passageways between the grain kernels. Transmission of sound in porous media is usually characterized by a fast and a slow wave.[12-14] The fast wave corresponds to propagation through the solid matrix of the porous elastic medium; the slow wave corresponds to propagation through the gas in the pores. The slow wave appears to predominate in grain, the fast wave being strongly attenuated, presumably because of friction between the grain kernels. To provide additional evidence to support this conclusion, tests were conducted with soft wheat immersed in different gases: air, argon and carbon dioxide. Pressure loading due to depth in the grain could perhaps cause the fast wave to appear by reducing frictional loss between the grain kernels, but tests reported here at simulated depths of about 3 m showed no evidence of this.

Because of differences in inter-kernel spacing, sound transmission will vary with the type of grain. Sound transmission was investigated in a number of common grains, specifically hard and soft wheat, brown rice, corn, soybeans and sorghum. Brown rice was tested because it is exported in this form. The

Fig. 1. Different grains tested in the sound transmission studies: (from left to right) soft wheat, sorghum, brown rice, soybeans and corn.

different grains are shown in Fig. 1. Hard wheat is not shown because of its similarity to soft wheat. Another factor that could affect inter-kernel spacing is pressure loading due to depth in the grain. Tests were performed on the effect of loading, simulating a depth of about 3 m. These showed no significant change in sound transmission. Loading pressure due to depth in bulk-stored grain has been studied since the beginning of the century.[15,16] For silos that have a height-to-width ratio of 3–5, about 80% of the load is on the floor and the remainder on the walls.[17] As the height-to-width ratio increases more load is transferred to the walls. The resistance of individual grain kernels to loading has been determined in grain-crushing tests.[18] The pressure required to crush a wheat kernel[18] is roughly from 10 to 25 kPa, which corresponds approximately to a 200–500 m wheat column. This is a conservative depth estimate which ignores the loading on the walls of the silo. Bulk density of grain in a bin is dependent on the filling method. It has been found that the bulk density in a bin filled with spreaders is 5–10% higher than in a bin filled with a vertical spout (Chang, personal communication 1995).

TEST FACILITIES AND EQUIPMENT

The sound-transmission studies were conducted at two locations: the National Center for Physical Acoustics (NCPA) at the University of Mississippi and the US Grain Marketing Research Laboratory (GMRL) in Manhattan, KS. At NCPA the tests were conducted in two tanks: a large tank $2.5\times1.3\times1.6$ m in size, with a volume of about 5 m^3, for tests with soft wheat, and a smaller tank $0.9\times1.8\times0.9$ m, with a volume of about 1.5 m^3, for tests with brown rice and soybeans. At GMRL tests were conducted with sorghum and corn in bulk-storage containers in an elevator building, and with hard wheat in a metal storage bin of about 105 m^3 capacity.

The test equipment, shown schematically in Fig. 2, is transportable and was used for all the tests. The speaker and two microphones are aligned horizontally at a depth of 0.5 m in the grain. The microphones are attached rigidly to a frame as shown in Fig. 2 and consist of a pair of phase-matched Bruel and Kjaer (B&K) 1/2 inch microphones, originally purchased for sound intensity measurement in the face-to-face arrangement with a solid spacer between the protection grids of the microphones. The protection grid prevents direct contact with the grain. The spacer is held in place by a piece of threaded rod protruding from each of the protection grids. In our tests the threaded rod was used to attach a conical end-piece to each microphone for easier penetration of the grain, as shown in Fig. 3. The effect of the conical end-piece on the sound field is the same as that of the spacer and hence it can be assumed that microphones are omnidirectional. The speaker is a 40-W Realistic 8-inch full-range speaker and is used as a source of continuous pseudo-random noise. The speaker is located inside a cylindrical housing

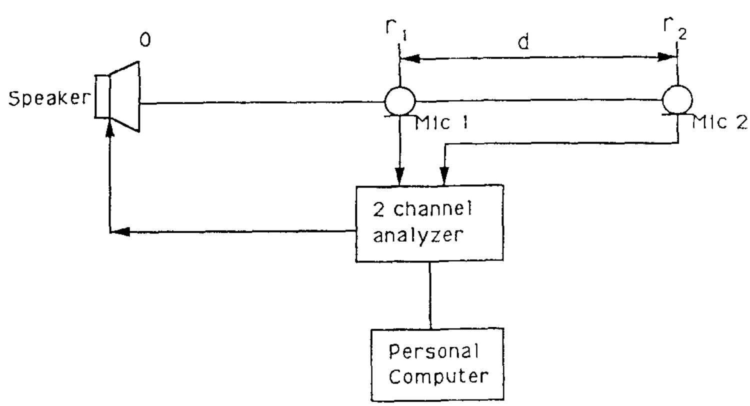

Fig. 2. Schematic drawing of the test equipment.

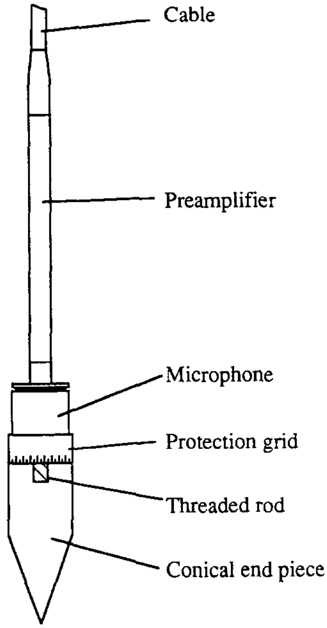

Fig. 3. Schematic drawing of conical end-piece attached to the microphone protection grid.

with holes to permit the passage of sound and is not in direct contact with the grain. The microphones are connected to a B&K 2032 two-channel analyzer controlled by a Hewlett-Packard 320 computer. The phase velocity c of sound transmitted between the microphones is determined by measuring the phase difference $\phi(f)$ between the two microphones, using the relation

$$c(f) = 2\pi f d/\phi(f) \tag{1}$$

where f is the frequency of the sound. The other quantity in the sound transmission studies, the attenuation coefficient $\alpha(f)$, was determined by measuring root-mean-square pressures, p_1 and p_2, at the two microphones and using the relation

$$\alpha(f) = 1/d \ \ln[r_1 p_1(f)/l r_2 p_2(f)] \tag{2}$$

where ln is the natural logarithm corresponding to the exponential law of decay of absorption in the grain and r_1 and r_2 are the distances from the speaker to the two microphones as shown in Fig. 2. The attenuation due to spherical spreading was also taken into consideration in this equation. The distances r_1, r_2 and separation d are related by $d = r_2 - r_1$. The separation d

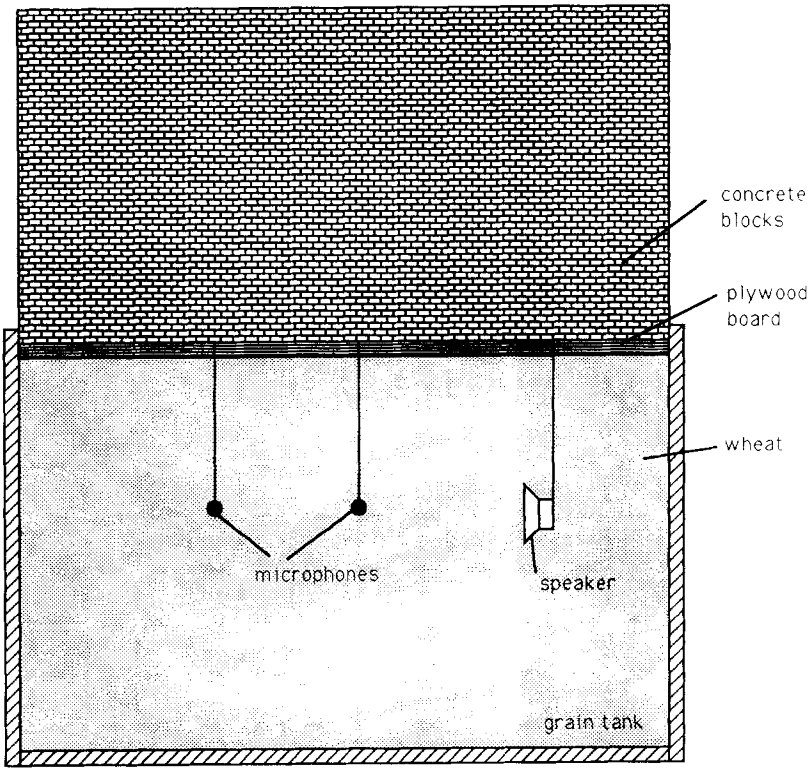

Fig. 4. Schematic drawing of loading of grain in large tank at NCPA using concrete blocks.

has to be known accurately for an accurate measurement of the sound velocity c. A fixture was made to hold the microphones 787.4 mm apart and 520 mm deep. The position of the speaker relative to the microphones could not be determined as precisely but this affects only the attenuation coefficient measurement. The error in speaker position was estimated to be about 25 mm which, for our measurements, is equivalent to a change in the attenuation coefficient of about 0.1. Because of the relatively large values of the attenuation coefficient, this was not considered to be a significant error.

In the large tank at NCPA it is possible to saturate the grain with gases more dense than air, such as carbon dioxide and argon. The tank is air-tight and covering the surface of the grain with nylon sheet keeps the ambient air from mixing with the more dense gas flowing through the grain. Tests were conducted with carbon dioxide and argon to determine the effect on sound transmission. The purpose of these tests is two-fold. First, they demonstrate that the sound is transmitted principally in the gas between the grain kernels.

Second, they support the validity of the analytical model used to fit the experimental data. The model determines the average size and tortuosity of the passageways between the kernels which should be independent of the gas.

The effect of grain compression due to depth was simulated by covering the surface of the soft wheat in the large tank at NCPA with plywood and loading it with concrete blocks, each weighing about 10.4 kg, as shown schematically in Fig. 4. The equipment shown in Fig. 2 was inserted through the plywood to measure the speed of sound and the absorption coefficient, for different loads of concrete blocks. The maximum load was 524 blocks, or a total weight of 5450 kg. The surface area was 2.78 m^2 so that the maximum pressure at the surface is 19.2 kPa, which is equivalent to a depth of about 2.7 m in wheat, to which is added the 0.5 m depth of the microphones. More realistic methods of determining the effect of depth were considered, such as pushing the microphones deeper into the grain. However, this would require longer rods for the microphones, making it more difficult to make an accurate determination of the separation distance d.

RESULTS

The results for soft wheat immersed in different gases in the large tank at NCPA are shown in Figs 5 and 6. These demonstrate that sound is transmitted mainly in the passageways between the grain kernels and not through the solid grain matrix. Figure 5 shows plots, as a function of frequency, of the speed of sound in soft wheat immersed, respectively, in air, argon and carbon dioxide. It is seen that the speed changes roughly in proportion to the adiabatic sound speeds of the gases at 300K, which are, respectively, 347, 334 and 271 m/s. In the passageways between the grain kernels, the speeds of sound are less than the adiabatic speeds of sound over a direct path between the microphones, principally because of the tortuosity of the transmission path. An additional reduction in sound speed occurs over the transmission path between the microphones, because of heat conduction and viscous drag between the gas and the grain kernels. In Figs 5 and 6 a fit of the experimental data is also shown (dashed lines) based on the analytical model of sound transmission in porous media described in the next section. It is seen that the overall fit of the data is quite good.

Results for the six different grains are given in Figs 7 and 8. The grains are, of course, immersed in air. To provide a clear distinction between the different grains in the figures, only fits of the experimental data provided by the analytical model are plotted, for speeds of sound in Fig. 7, and for the attenuation coefficients in Fig. 8. As expected the larger grains, soybeans and

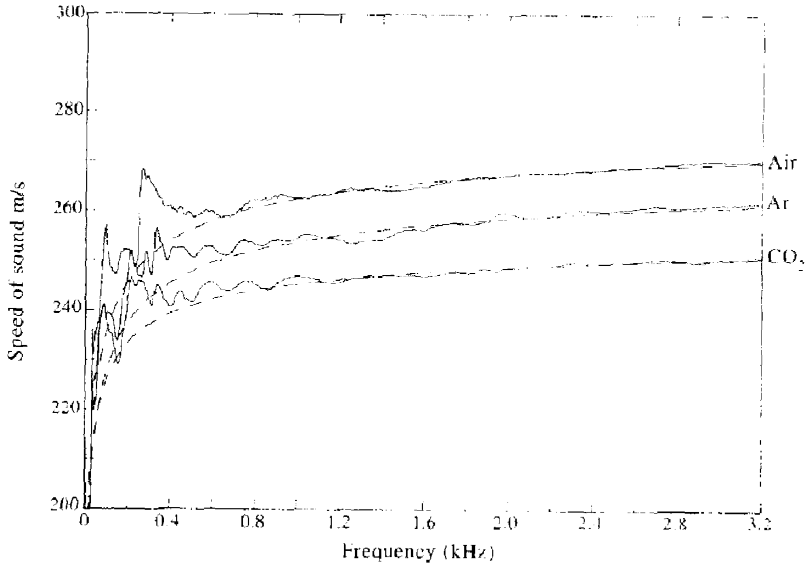

Fig. 5. Plots of speed of sound, as a function of frequency, in soft wheat, immersed in air, argon and carbon dioxide. The dashed lines are fits of the experimental data using the analytical model.

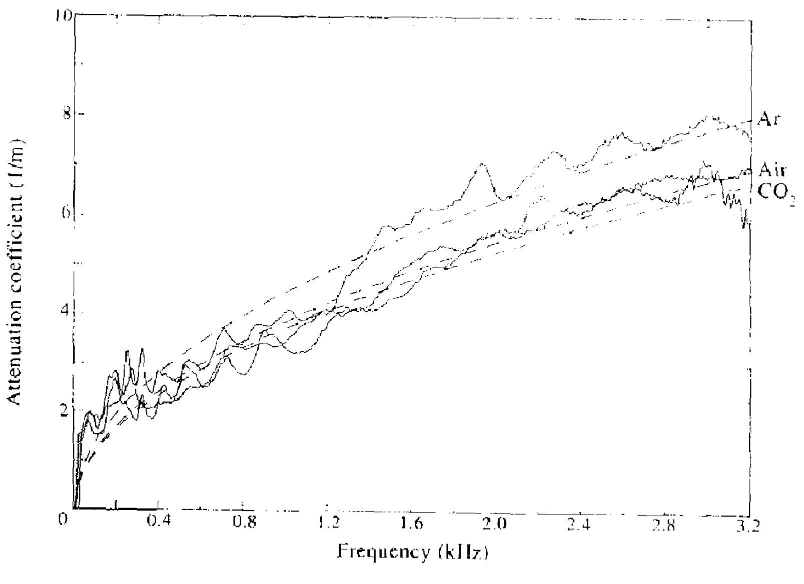

Fig. 6. Plots of attenuation coefficient, as a function of frequency, in soft wheat, saturated with air, argon and carbon dioxide. The dashed lines are fits of the experimental data using the analytical model.

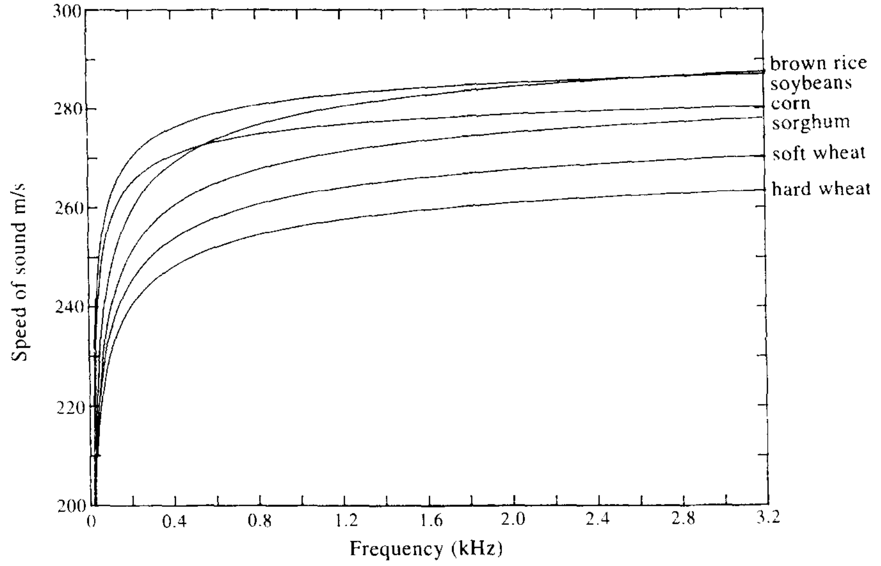

Fig. 7. Plots of fits of the experimental data, using the analytical model, for the speed of sound, as a function of frequency, in hard wheat, soft wheat, sorghum, brown rice, soybeans and corn.

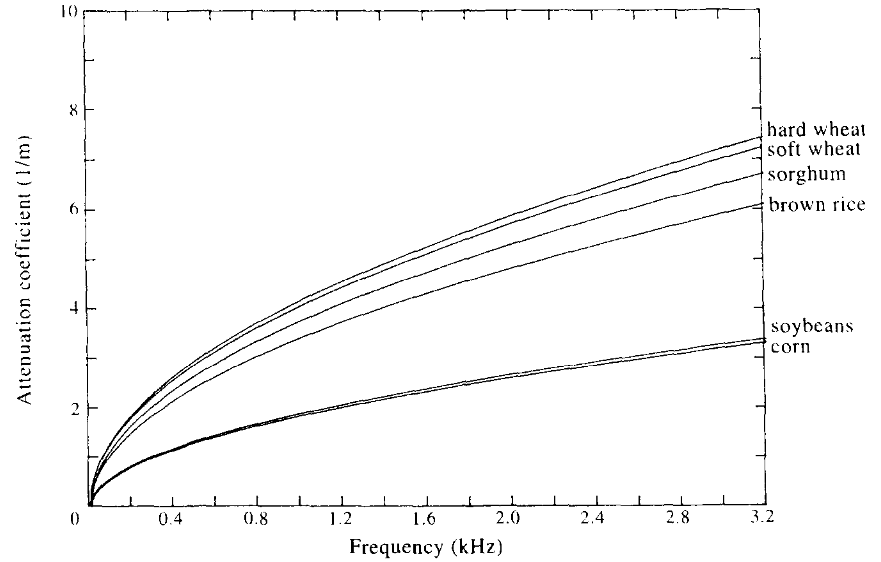

Fig. 8. Plots of fits of the experimental data, using the analytical model, for the attenuation coefficient, as a function of frequency, in hard wheat, soft wheat, sorghum, brown rice, soybeans and corn.

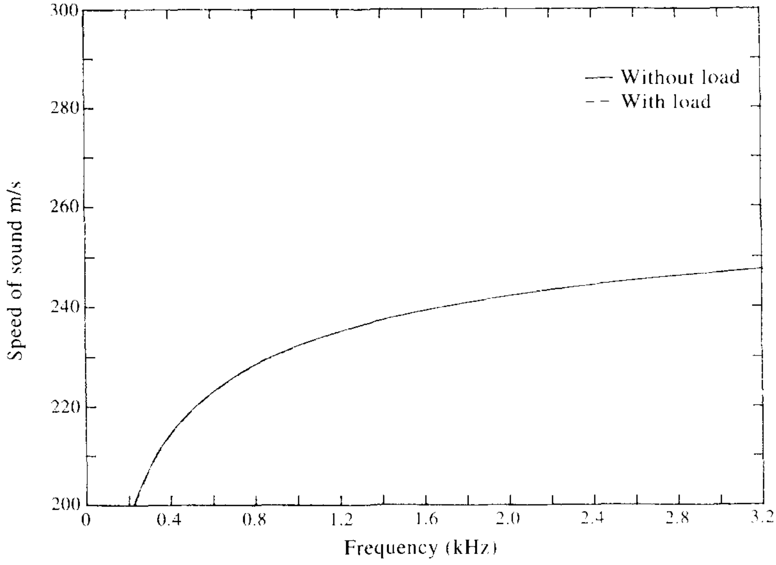

Fig. 9. Effect of loading on the speed of sound in the soft wheat. The plots are fits of the experimental data using the analytical model.

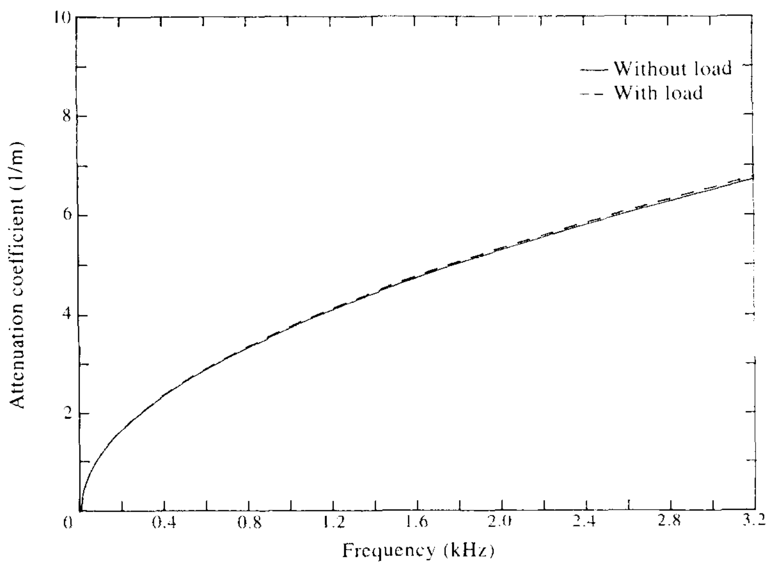

Fig. 10. Effect of loading on the acoustical attenuation coefficient of soft wheat. The plots are fits of the experimental data using the analytical model.

corn, have a smaller absorption coefficient than the other grains because of larger passageways between the grain kernels.

Figures 9 and 10 show the effect of loading on the speed of sound and the attenuation coefficient for soft wheat in the large NCPA tank. Again only fits of the experimental data with the analytical model are plotted. The loading is equivalent to a depth of wheat of 3.2 m at the microphones. It is seen that there is very little difference in sound transmission between the unloaded and loaded conditions, indicating that the size and tortuosity of the passages between the grain kernels is not changed significantly. It is possible that the passages remain unchanged as loading or depth is increased. The first significant change that would then occur is when loading fractures the grain kernels which, as shown earlier, happens when the depth is roughly 200 m or more. As indicated earlier, increased loading can also reduce frictional losses in the grain and cause sound to be transmitted through the solid grain matrix. Additional tests at much greater depths are required to determine whether or not this occurs.

ANALYSIS OF RESULTS

Simple theories of sound transmission through porous media are based on the transmission of sound through rigid, narrow, cylindrical pipes whose diameter represents an average spacing between grains.[19–21] That the sound does not travel along a straight path is accounted for by a tortuosity factor, which is the ratio of the length of the actual path to the length of the straight path. This model requires the following thermodynamic quantities for the gas in the grain:

(1) the adiabatic speed of sound in free space, c_0;
(2) the ratio of specific heats, γ;
(3) the kinematic viscosity $\nu = \mu/\rho$, where μ is the viscosity and ρ is the density;
(4) the thermal diffusivity $\kappa = k/\rho C_p$, where k is the thermal conductivity and C_p is the specific heat at constant pressure.

We first apply the theory to the transmission of sound through soft wheat immersed in different gases. The gas in the wheat is assumed to be at atmospheric pressure and 300K. For these conditions, the thermodynamic quantities for the gases used in the tests are listed in Table 1. In the theory the first four quantities in the table are combined in the following expression F, given in the last column of Table 1

TABLE 1
Thermodynamic Properties of Different Gases

Gas	c_0 *(m/s)*	γ	ν *(m²/s)*	κ *(m²/s)*	F *(m²/s)*
Air	347	1.4	1.57×10^{-5}	2.21×10^{-5}	0.56×10^{-2}
Argon	334	1.67	1.40×10^{-5}	2.09×10^{-5}	0.61×10^{-2}
Carbon dioxide	271	1.3	1.13×10^{-5}	1.09×10^{-5}	0.42×10^{-2}

$$F\sqrt{\nu}+\left(\sqrt{\gamma}-\frac{1}{\sqrt{\gamma}}\right)\sqrt{\kappa} \tag{3}$$

where F is used to determine the radius r and the speed of sound c in the pipe, from the equations

$$r=\sqrt{\pi f}F/\alpha c_0 \tag{4}$$

$$c=c_0/[1+F/2r\sqrt{\pi f}] \tag{5}$$

where α is the attenuation coefficient defined in eqn 2. Equations 4 and 5 were obtained from Zwikker and Kosten.[19] The measured speed of sound c_m and measured attenuation coefficient α_m in Figs 5 and 6 are related to c and α in eqns 4 and 5 by the tortuosity factor τ using the relations

$$c_m=c/\tau \tag{6}$$

$$\alpha_m=\alpha\tau \tag{7}$$

From eqns 3–7, a fit was determined for the measured data for different gases, shown by the dashed lines in Figs 5 and 6. The theory in eqns 3–7

TABLE 2
Acoustic Transmission Properties of Different Gases in Soft Wheat

Gas	2r *(mm)*	τ
Air	0.61	1.33
Argon	0.63	1.37
Carbon dioxide	0.59	1.26

TABLE 3
Acoustic Transmission Properties for Different Grains from the Analytical Model

Grain	*Pipe diameter (mm)*	*Tortuosity*	*Estimated detection range (m)*	
Soft wheat	0.61	1.33	0.10[a]	0.50[b]
Hard wheat	0.61	1.40	0.10	0.49
Brown rice	0.65	1.16	0.10	0.55
Corn	1.34	1.28	0.12	0.82
Sorghum	0.60	1.25	0.10	0.52
Soybeans	1.30	1.23	0.12	0.81

[a]Based on measured insect detection range in Vick *et al.*[9] and Hagstrum *et al.*[10]
[b]Based on measured insect detection range given by Hickling and Webb (unpublished data 1992).

represents a high-frequency–low-resistivity approximation so that the fit is correspondingly better at higher frequencies. The fits for the different gases were obtained using values of the pipe diameter $2r$ and the tortuosity factor τ given in Table 2 which shows a variation of $\pm 4\%$ for the pipe diameter, or average spacing between grains, and $\pm 5\%$ for the tortuosity. The agreement is quite good, indicating that the geometry of the grain matrix remains essentially unchanged for the different gases. Since this is what would be expected, it provides additional support for the effectiveness of the model. These results can also be used to show that the reduction in sound speeds in Fig. 5 below the adiabatic speeds of sound in Table 1 is due to the tortuosity, combined with heat conduction and viscous resistance in the narrow passageways between the grain kernels over the transmission path between the microphones.

The analytical model was used to determine the pipe diameters and the tortuosities for the different grains, from fits to the experimental data shown in Figs 5–8. These are listed in Table 3. Also included in the table are estimates of the detection range for different grains determined from measured insect detection ranges of 0.1 and 0.5 m in soft wheat (Hickling and Webb, unpublished data, 1992; see also Vick *et al.*[9] and Hagstrum *et al.*[10]). Assuming the measured detection range in soft wheat at the head of the column in Table 3, the detection range in the other grains is determined from the attenuation coefficient at 1 kHz relative to the attenuation coefficient of soft wheat. When the range is relatively short (~ 0.1 m) the principal attenuating effect is spreading loss. When the range is longer (~ 0.5 m) the principal attenuating effect is absorption in the grain. It is seen that the pipe diameter and the estimated detection range are greater for corn and soybeans, as would be expected from the size and shape of the grains in Fig. 1. As indicated earlier, for a given ratio of sampling volume to total grain volume, the total number of acoustic sensors distributed along cables immersed in the grain, is inversely proportional to the cube of the insect detection range of the sensors. Hence, for a detection range of 0.1 m, soybeans and corn would require about 40% fewer sensors than soft wheat. However, if the detection range is 0.5 m, 5 times fewer sensors would be required in soybeans and corn than in soft wheat.

CONCLUDING COMMENTS

Grain is a highly absorbing acoustical medium. Sound is transmitted principally through the gas in the narrow passageways between the grain kernels. Transmission through the solid grain matrix appears to be almost non-existent, presumably because of friction between the kernels. Pressure loading, due to depth in the grain, appears to have little effect on sound transmission, up to depths of several meters.

Information required for acoustic detection of insects in grain can be summarized as follows. Grain acts as an acoustical low-pass filter, the attenuation coefficient increasing as the square root of sound frequency. Strong absorption of sound in grain reduces background noise, but limits the range at which insects can be detected. In previous work the insect detection range in wheat was measured to be somewhere between 0.1 and 0.5 m. Greater detection range can be achieved at low frequencies because of lower absorption. Greater detection range can also be achieved when the passageways between the grain kernels are larger and the attenuation coefficient is correspondingly reduced, for example, with soybeans and corn. Existing systems for detecting insects in bulk-stored grain use a sampling procedure with acoustic sensors distributed along cables immersed in the grain. The number of sensors required for a given ratio of sampling volume to total grain volume is inversely proportional to the cube of the insect detection range of the sensors. Increasing the range of the sensors therefore greatly increases the effectiveness of the detection system.

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